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Radio continuum and CO emission in star-forming galaxies.

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We combine the radio continuum images from the NRAO VLA Sky Survey with the CO-line observations from the extragalactic CO survey of the Five College Radio Astronomy Observatory to study the relationship between molecular gas and the star formation rate within the disks of 180 spiral galaxies at 45 resolution. We find a tight correlation between these quantities. On average, the ratio between the radio continuum and the CO emission is constant, within a factor of 3, both inside the same galaxy and from galaxy to galaxy. The mean star formation efficiency deduced from the radio continuum corresponds to convert 3.5% of the available molecular gas into stars on a time scale of 10^8 yr and depends weakly on general galaxy properties, such as Hubble type or nuclear activity. A comparison is made with another similar analysis performed using the H_α luminosity as star formation indicator. The overall agreement we find between the two studies reinforces the use of the radio luminosity as star formation rate indicator not only on global but also on local scales. radio continuum: galaxies – galaxies: spiral – ISM:molecules – stars:formation

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Introduction One of the major goals of the studies of external galaxies is understanding the relationship between the star formation rate (SFR) and the physical condition in the interstellar medium. Several indicators have been suggested to estimate the SFR (of massive stars) in galaxies. These include the U-band magnitude, the strength of Balmer lines emission, the far-infrared (FIR) emission and the radio luminosity; the rates inferred from the different indicators span almost four orders of magnitude going from 10^{-2} to 10^2 $M_\odot$ yr^{-1}. Cram et al. (1998) checked the consistency between the SFR deduced from the U-band, H_α, FIR and radio luminosity using a sample of 700 local galaxies. They noted that there are systematic differences between these various indicators. In particular they suggested that the H_α luminosity may underestimate the SFR by approximately an order of magnitude when the SFR is ≥ 20 $M_\odot$ yr^{-1}. They concluded that the radio continuum luminosity at decimeter wavelengths of a star forming galaxy provides a better way to estimate the current rate of star formation. The radio continuum emission at 1.4 GHz from a star-forming galaxy is mainly synchrotron radiation produced from relativistic electrons accelerated by supernovae explosions (Lequeux 1971). Indeed the radio continuum luminosity appears to be directly proportional to the rate of formation of supernovae (Condon 1992). This view is reinforced by the tight correlation existing between the radio luminosity and the FIR for spiral galaxies (see e.g. Condon 1992). Since the radio continuum at 1.4 GHz does not suffer significant extinction, the radio luminosity constitutes a very useful tool to determine the current SFR in a spiral galaxy.

Since the discovery that stars form in molecular clouds, it is essential to determine, not only the rate, but also the efficiency of conversion of the interstellar gas in stars; i.e. the star formation efficiency (SFE). The SFE measures the formation rate of young stars per unit of mass of gas available to form those stars. Determining the SFE is important to distinguish a situation in which a high SFR indicates a higher efficiency in converting gas in stars rather than a higher gas quantity.

The CO molecule luminosity and the virial mass of giant molecular clouds correlate very well in our Galaxy and in other nearby spirals (Young & Scoville 1991 and references therein). The comparison of different SFR tracers with the mass of molecular clouds provides indeed an important tool to investigate the behaviour of the SFE within and among galaxies. Many studies have been concerned with the behaviour of the star formation process on global scales, averaged over the entire star-forming disk. These works showed that the disk-averaged star formation process is well described by a Schmidt (1959) law of the type $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^N$, where $\Sigma_{\rm SFR}$ and $\Sigma_{\rm gas}$ are the observable surface density of SFR and total (atomic + molecular) gas density, respectively, and the exponent N typically ranges from 1.3 to 1.5 (Kennicutt 1998).

An interesting development of these global studies, the investigation of the behaviour of the SFE *within* the disks of the individual galaxies, provides much physical insight into the star formation process itself. The extragalactic CO survey of the Five College Radio Astronomy Observatory (Young et al. 1995, hereafter FCRAO CO Survey) provided a uniform database of CO data for 300 galaxies at a resolution of 45, opening the possibility to extend the study of the Schmidt relationship of the SFR versus the H_2 density over the same physical regions well inside the galaxy disks. Since the star formation process involves the molecular gas directly, some authors recognized that the determination of the Schmidt law assumes a clear physical meaning if restricted to this gas component. Moreover, in the considered regions the molecular gas is dominant over the atomic one and, contrary to this latter, its azimuthally averaged distribution follows closely the radial profiles of the main SFR indicators (Tacconi and Young 1986, Young & Scoville 1991). Rownd & Young (1999; hereafter RY99) conducted an H_α imaging of 121 of these galaxies, determining the local relationship between the SFR and the molecular gas. They found a correlation between these two quantities and concluded that for face-on spiral, in general, there are no strong SFE gradients across the star-forming disks. The majority of large SFE variations they found are seen between adjacent disk points, reflecting regional differences in the SFE, and any radial gradients are at most a secondary effect. In contrast, they pointed out that consistent radial variations (up to an order of magnitude or more) of the SFE exist within many highly inclined galaxy disks. They attributed the decreasing SFE towards the centers of these galaxies to a large amount of dust extinction on the H_α luminosity.

Adler et al. (1991) found a correlation between the radio continuum flux density at 20 cm and the CO line emission on global scales for a sample of 31 spiral galaxies. They also studied the relationship of these two quantities within the disks of 8 nearby well resolved spiral galaxies, finding that their ratio is constant both inside the same galaxy and from galaxy to galaxy.

The work we present here is complementary to the analysis of RY99 and extends that of Adler et al. (1991). We combined the radio continuum images at 1.4 GHz from the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) with the FCRAO CO survey to study the relationship between the radio continuum and the molecular gas point-to-point within the disks of 180 star-forming spiral galaxies. It is important to stress that we are comparing two homogeneous data set with the same angular resolution of 45.

The paper is organized as follows: in Sect. 2 and Sect. 3 we present the sample used and we describe the data analysis, respectively. In Sect. 4 we present the results of the statistical analysis and in Sect. 5 we discuss the results obtained.

We use a Hubble constant H_0=50 km s^{-1}Mpc^{-1} throughout the paper.

Sample selection To investigate the star formation law within the disks of normal galaxies, we combined the data from two public surveys. We use the NVSS for the radio continuum and the FCRAO CO survey for the molecular gas, respectively.

The NVSS was performed at 1.4 GHz with the Very Large Array (VLA) in D configuration. It has an angular resolution of 45 (FWHM), a noise level of 0.45 mJy/beam (1σ) and covers all the sky north of declination –40. The shortest baseline is 35 m, corresponding to $\simeq$167λ, therefore structures up to about 10 in angular size are properly imaged.

The FCRAO CO survey comprises 300 galaxies observed along the major axis of the disk for a total of 1412 locations. Most of the galaxies in the survey are spirals or irregulars north of declination –25. At the frequency of the CO $J = 1-0$ transition (115.27 GHz) the FWHM of the 14-m FCRAO telescope is 45. The weakest line detected depends on the width of the line, and hence on the velocity field within the beam. The uncertainties on the individual line intensity vary from galaxy to galaxy. A conservative estimate of the rms noise, including the calibration, baseline removal, and the rms noise per channel is about 25% (the median signal-to-noise ratio is 4).

We note that the two surveys have uniform sensitivity and identical angular resolution. This fact circumvents the difficulties deriving from the comparison of data from multiple instruments or studies which are subtly incompatible either because of inconsistent signal-to-noise ratios or unmatched resolution.

The original FCRAO CO survey includes 300 galaxies selected from the RC2 (de Vaucouleurs et al. 1976) or the *IRAS* database satisfying at least one of the following criteria: i) $B^0_{\rm T} < 13.0$, ii) $S_{60} > 5$ Jy or iii) $S_{100} > 10$ Jy. Although the FCRAO CO survey is not a complete sample in terms of flux-density or volume limit, the observed galaxies cover a wide range of luminosity, morphology and environments. For this reason they represent an ideal database to study the behaviour of the star formation process and the molecular gas in a wide variety of conditions.

Since our interest was primarily to investigate the behaviour of star formation within the galaxy disks, we have selected, from the FCRAO CO survey, a sub-sample of 180 objects for which there were at least three different observations of the CO line in the disk.

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